Armed Services Technical Information Agency

AD 40092

UNCLASSIFIED

PRELIMINARY REPORT ON THE MINIMIZATION

OF DRIFT IN MAGNETIC CONTROL AMPLIFIERS

28 JANUARY 1954

U. S. NAVAL ORDNANCE LABORATORY

WHITE OAK, MARYLAND

NAVORD Report 3595

PRELIMINARY REPORT ON THE MINIMIZATION OF DRIFT IN MAGNETIC CONTROL AMPLIFIERS

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ABSTRACT: All magnetic control amplifiers exhibit null drift under temperature, supply voltage, and frequency variations. Many applications specify such a low level of drift that special techniques are demanded in the design and construction of the amplifier. Tests, specifications, and procedures for the practical manufacture of drift insensitive magnetic control amplifiers are given. Conservative estimates of the yields on components are made.

The techniques outlined are applicable to all high performance magnetic control amplifiers and constitute a less complex manufacturing schedule than some practical procedures now used in this field.

In following these techniques, amplifiers have been consistently produced with drifts below 0.125 microwatt (0.05 volts at 20,000 ohms input impedance) for a temperature range of $-55^{\circ}C$ to $+71^{\circ}C$, voltage range of 115 volts $\pm$ 10 volts and frequency range of 400 cps $\pm$ 40 cps.

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Under Bureau of Ordnance assigned tasks NOL-Re8-1-2-53 and
NOL-A8f-1-2-54 for the development of magnetic amplifiers,
the problem of null drift in the half-wave magnetic control
amplifiers such as those reported in NavOrd Reports No. 2737
and No. 2833 was investigated. As requested verbally by
Mr. Ensinger, Re8, the effort was directed toward the minimi-
zation of drift in a specific circuit and the development of
the tests and procedure necessary for the practical production
of this magnetic amplifier.

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                    By direction

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PRELIMINARY REPORT ON THE MINIMIZATION
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INTRODUCTION

1. Drift is herein defined as output from the magnetic
control amplifier for zero input due to the influence of
changes in ambient temperature, voltage and frequency. In
a closed loop position control system where the output of
the controller tends to remain zero, drift in the magnetic
control amplifier results in a null error being present on
the input terminals. Both open and closed loop methods of
measuring drift are employed in this report and will be
justified in each case.

2. The magnitude of drift considered also should be stated
at this point. Experience seems to indicate that by employing
completely unmatched rectifiers and unmatched Orthonol tape
cores selected at random, drift may be encountered equivalent
to a signal input of a volt or greater at an input impedance
of 10,000 ohms. With nominal selection of components, drift
for a temperature range of approximately $-55^{\circ}C$ to $+71^{\circ}C$, line
voltage of 115 volts $\pm$ 10 volts, and frequency of 400 cps
$\pm$ 40 cps can be reduced to the order of 0.2 volts. This
report deals with the matching techniques useful in reducing
the drift to below the 0.125 microwatt level (0.05 volt at
20,000 ohm input impedance).

3. In investigating this drift problem and seeking a practi-
cal solution a specific magnetic amplifier circuit was
selected. This was done in order to indicate the manufactur-
ing problem and its solution through various tests and
procedures, and to estimate probable yields on components. A
high performance magnetic control amplifier circuit was selec-
ted in which the effects of drift were more readily apparent.
In addition, part of the circuit comprised an integrator in
which it was necessary to maintain essentially unity gain
under all conditions. This placed tight restrictions on the
slope and linearity of the gain curve.

4. The techniques described in this report were designed to
provide a practical manufacturing procedure which would be
simple and also give a high yield on all components. These
techniques are applicable to all high performance magnetic
control amplifiers. In instances where the gain is not
required to remain constant, the specifications can be loos-
ened considerably.

SYSTEM REQUIREMENTS

5. The specific magnetic control amplifier circuit investigated is shown in figure 1 along with the closed servo loop. The amplifier consists of four half-wave type stages.[1] Positive integral feedback is placed around the first two, forming an integrator for unity loop gain around the two stages.[2] The system is designed for use with Bureau of Ordnance Servo Motors Mark 12 and Mark 16. Speed proportional voltage from the tachometer generator is fed back to the input of the third stage supplying damping for the system. The synchro error detection system produces 1 volt per degree error.

6. In the closed loop servo system the integrator provides a near-zero velocity error with infinite static accuracy, exclusive of synchro error and drift error. The static error was required to be less than 0.05 volts and the velocity error, including static error was not to exceed 0.1 volts for rotational speeds at the synchro control transformer of up to 20 degrees per second. The maintenance of a low velocity error requires a constant and linear gain in Stages I and II that is unaffected by variations in temperature, voltage and frequency. In many respects this is a more difficult part of the problem than the actual drift and is considered here because it is a requirement frequently placed on high performance amplifiers, both electronic and magnetic. Solution of this portion of the problem causes the drift problem solution to be even more general and useful.

6. The system was required to operate over the temperature range of -55°C to +71°C and from a line voltage of 115 volts + 10 volts at a frequency of 400 cps + 40 cps. For the purposes of this investigation it was assumed that line frequency variations could be simulated by additional line voltage variations. Subsequent spot checks supported this assumption. Consequently the line voltage was varied from 100 to 130 volts to simulate both voltage and frequency variations. Under all combinations of conditions the drift was consistently held below the 0.05 volt level and the gain was stabilized so as to allow no more than 0.1 volts velocity error (including drift error) for the input velocities indicated.

OUTLINE OF PROCEDURE

7. In brief outline the technique for the minimization of drift in magnetic control amplifiers is as follows:

(A) Select Stage I rectifiers. This requires the constrution of a simple test circuit whereby the rectifiers are

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are evaluated by two meter readings. The yield in this test is estimated to be approximately 30% and all rejects will be utilized elsewhere in the circuit.

(B) Select Stage I reactors by using the test circuit of (A). The reactors are paired on the basis of two meter readings. Specified E-I curves for all Stage I reactors must fall within a certain range of values. These curves are obtainable with nominally good core material and should be specified in purchasing. When cores are obtained in this manner there should be no rejects.

By use of the above selected components with some additional precautions the drift in Stage I can be reduced to the order of less than 0.1 volt.

(C) Select Stage II rectifiers. This is accomplished in a test circuit which permits rapid measurement and sorting as to characteristics. From these sorted rectifiers matched pairs can be chosen. From large quantities of rectifiers yields in the order of 80% or higher can be obtained with all rejects being utilized in the third stage.

(D) Select Stage II reactors. These should be matched by weight to the third significant figure and have E-I curves that fall in a certain range of values. These properties are obtainable with nominal Orthonol tape cores and if some restrictions are placed on purchasing should result in yields in the order of 95%. All rejects excepting total failures can be utilized in Stage IV.

The above selected components can be used to reduce the drift in Stage II to below the 0.1 volt level.

(E) With the stages assembled the drift curve of each over the temperature range is plotted. A Stage I and a Stage II whose drifts are in the same order of magnitude are connected so that the drifts oppose each other. This insures a drift in the first two stages of below the 0.05 volt level. The yield in stages should be 95% or higher when large numbers of stages are built.

8. The drift associated with the third and fourth stages has been found to be negligible when nominal care is taken in obtaining components. Thus the 0.05 volt drift associated with the first two stages represents the maximum drift in this four stage magnetic control amplifier.

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SELECTION OF RECTIFIERS FOR STAGE I

9.   It was found that for very accurate matching of rectifiers
the exact operating conditions in the circuit must be dupli-
cated in the testing circuit. Also the sensitivity of the
testing circuit had to be of a very high order to detect suf-
ficiently small differences in the rectifiers. For these
reasons a comparison type rectifier matching circuit was con-
structed in which pairs of rectifiers are checked against each
other. The reactors used in the test circuit are of the same
type as those used in the completed amplifier stage.

10.   The construction of the rectifier testing circuit is as
follows:

     (1) Select a pair of 4-79 molybdenum permenol cores,
matched by weight to the third significant figure.

Specifications: 1-1/2" O.D. 1-1/8" I.D. 8 mil laminations,
insulated by 1 mil paper, total 12 laminations.

     (2) Sector wind with the following windings:

          800 turns #35   (Winding A)

          800 turns #29   (Winding B)

          800 turns #29   (Winding C)

          800 turns #35   (Winding D)

The distribution of windings is shown in figure 2.

     (3) Connect in differential circuit as shown in figure 3.
Note that no balancing is used. Components should be chosen
such that without desensitizing the meter, meter A does not
read off scale.

     (4) Calibrate meter A by placing 0.05 volts d.c. on the
signal input terminals. If meter A has an internal impedance
of approximately 550 ohms the change in output current should
be in the order of 8 microamperes.

     (5) With the rectifiers under test in positions #1 and
#2 note the unbalance reading on meter A.

     (6) Interchange rectifiers #1 and #2 and again read
unbalance on meter A.

(7) The algebraic difference in the readings of step (5) and step (6) must not exceed four times the magnitude of the calibrated change in output current noted in step (4) for the rectifiers to be sufficiently matched.

11. The circuit rectifiers in Stage I are 5/8" square 6 plate half-wave connected selenium rectifiers. Radio Receptor Company rectifiers, which were immediately available in quantity, were used in the study of the drift problem and gave the desired results. Other rectifiers may be substituted so long as amplifier performance (gain and time delay) are unimpaired. In general, the highest reverse to forward impedance possible at 400 cps power frequency is preferred.

12. Before matching, the rectifiers must be temperature cycled ten times from -60°C to +75°C and afterwards formed for 24 hours at rated current and voltage. Care must be exercised in soldering connections to these rectifiers after they have been matched because undue local heating of this type may change their characteristics.

SELECTION OF CORES FOR STAGE I

13. Laminated core material was chosen for the cores of Stage I to minimize the sensitivity to strains over the temperature range. The material is 4-79 molybdenum permenol. The cores are constructed of 8 mil laminations insulated by 1 mil paper having inside diameter of 1-1/8 inches and outside diameter of 1-1/2 inches. A total of 12 laminations are used. The cores to be matched should come from the same heat treating anneal and be matched by weight to the third significant figure. Sufficient paper should be inserted in the core box to prevent excessive movement of the laminations, although binding of the laminations in the box is to be avoided.

14. The cores are then sector wound with

    800 turns #35   (Winding A)

    800 turns #29   (Winding B)

    800 turns #29   (Winding C)

    800 turns #35   (Winding D)

as shown in figure 2. After winding, the reactor is vacuum impregnated in medium weight oil of fairly constant viscosity such as hydraulic oil. It is not necessary to temperature cycle these cores.

15. The wound reactor when checked on the test set-up of
figure 4 using 800 turns should have an E-I curve in the
range shown in figure 5. This measurement is not sufficiently
sensitive to be used as a matching test but rather is used to
insure the necessary gain in the first stage. Consequently,
the E-I curve of the reactor must be as good as the range
indicated.

16. In order to facilitate purchase of these cores, the d-c
data is given. Sufficient correlation has not been obtained
to guarantee that duplication of the d-c data will necessarily
produce the E-I curve required. However the d-c data should
be of the following order:

Maximum permeability = μ max = 700,000 to 800,000

Coercive force (H_c) = .0045 oersteds

Maximum flux density = 7800 - 7900 gauss

Residual flux density = 5100 - 5300 gauss

17. The wound reactors are matched in pairs in the test set-
up of figure 3. A set of fairly well-matched rectifiers are
required from the rectifier matching test. Provision must be
made for the insertion of the reactors into the circuit and
for interchanging them. With the reactors in the circuit the
unbalance is noted on meter A. Then the reactors are inter-
changed and the unbalance reading again noted. The algebraic
difference of these two unbalances must not exceed twice the
magnitude of the calibrated output for 0.05 volts d.c. input.

SELECTION OF RECTIFIERS FOR STAGE II

18. The selenium rectifiers for Stage II are composed of 8
plates one inch square, doubler connected with plates in
intimate contact. Before testing they are temperature cycled
ten times between -60°C and +75°C and then formed for 24 hours
at rated current and voltage. Care must be exercised in
soldering connections to these rectifiers after they have been
tested as undue local heating of this type may change their
characteristics.

19. The rectifier characteristics are measured in the circuit
of figure 6. An rms voltage of 15 volts is applied and the
half-wave average current is regulated, by the variable resist-
ance, R, to 30 ma. This simulates to some extent actual cir-
cuit conditions. The circuit in series with the rectifier
under test gives a measure of reverse leakage current while
the circuit in parallel with the rectifier under test gives a

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measure of the forward voltage drop. The germanium diodes used are General Electric type IN92, selected to have less than 45 microamperes leakage current with 45 volts d.c. applied in the reverse direction. The microammeters and milliammeter are adjusted to read on scale (preferable mid-scale) whereupon the test circuit is ready to indicate relative values of the rectifiers to be tested. More elaborate calibration could be made so as to indicate actual values of current and voltage but this is not necessary. If desired, the error due to leakage currents in the germanium diodes can be reduced by placing the germanium diodes in dry ice. However again this is not necessary. Each four plate section of the doubler connected rectifier is now tested. Figure 7 shows a pair of doubler connected rectifiers and the sections that must be matched. Two sections are considered matched if the microammeter readings (proportional to reverse current) agree within 4 microamperes, and the milliammeter readings (proportional to forward voltage drop) agree within 0.04 milliampere. If the sensitivity of the two meters is increased better matching can be obtained but this will probably not be necessary unless the temperature sensitivity of the rectifiers used is greater than those so far encountered.

SELECTION OF CORES FOR STAGE II

20. If commercially selected cores are available in which the coercive forces and remanences are matched, these should be obtained. In general however unmatched cores will be purchased in which case the selected set should be matched in weight to the third significant figure. The real test as to their acceptability is that an E-I curve taken on the test set-up shown in figure 4 using 2200 turns must fall in the range of values indicated in figure 8. This specifies the gain properties of the core as well as relative matching.

21. In order to simplify the production and selection of cores that will have the above specified E-I curves when wound and tested the following heat treatment is indicated. This heat treatment is used successfully on a laboratory scale at the Naval Ordnance Laboratory and will serve as a guide to producing the desired cores.

22. An alloy of 50% nickel, 50% iron is cold reduced approximately 99% to .002" tape. While being wound into a toroidal tape core it is insulated in a mixture consisting of 200 grams of magnesium hydroxide, 5.25 grams of Lomar PW and 2 liters of water passed through a coloid mill. Then it is rapidly heated to 975°C (requiring approximately 15 minutes) in a pure hydrogen atmosphere. After being held at this temperature of

975° for two hours it is rapidly cooled by being withdrawn from the furnace heat zone. The core temperature should fall below 200°C in approximately 20 minutes.

23. The heat treatment will vary slightly with different amounts of impurities in the alloy and with different amounts of cold reduction. In general the d-c properties obtained in the cores will be as follows:

Maximum permeability (μm) = 85,000

Coercive force (H_c) = 0.15 oersteds

Ratio of residual flux density to maximum flux density $\left(\frac{Br}{Bm}\right) \approx .93$

24. Again it should be noted that the above properties can not be used as a guarantee that the wound reactor will possess the specified E-I curves since complete correlation has not yet been obtained between the above d-c properties and the dynamic performance of the cores in a magnetic amplifier circuit. The above procedure and values will however serve as a help to the manufacturer in producing the desired cores.

25. It should be made clear that the properties demanded of the cores in the second, third and fourth stages are those possessed by nominally good square loop core material manufactured commercially under the names of Orthonol, Orthonik, Deltamax, etc. No difficulty should be experienced in purchasing these cores. They are usually obtainable in phenolic core boxes with some packing such as silicone grease to prevent excessive movement.

26. Before they are tested, the wound reactors should be temperature cycled over the required temperature range to be sure the necessary expansion and contraction is obtainable and to produce any permanent strains that will result from normal usage.

27. A recommended procedure is to take the reactors through ten temperature cycles from -60°C to +75°C.

28. Summarizing, the selection of cores for Stage II involves the following:

(1) Select cores in sets of two by matching their weights to the third significant figure.

(2) Wind the cores with the prescribed windings and temperature cycle the wound reactor ten times from -60°C to + 75°C.

(3) Check to see if the H-I curve falls in the prescribed range.

29. The tape wound toroidal core size used is 1-1/8" inside diameter, 1-3/8" outside diameter, 1/4" tape width. The tape thickness is .002". The same core size is used in the third and fourth stages allowing the use of rejects from the second stage with the necessary modification of windings.

ASSEMBLY AND TESTING OF STAGE I

30. After selection of the rectifiers and reactors according to the above procedure, Stage I is assembled. To test Stage I, it is cascaded with a "standard" second stage which is known to be fairly well-balanced. This test connection is shown in figure 9.

31. While connected in this manner Stage I is trimmed for voltage insensitivity. The circuit is first balanced for zero output (with the input terminals shorted) by placing a high resistance across one of the 800 turn windings on one of the reactors. Trial and error will show which reactor must be shunted to zero the output. The line voltage is then varied over the desired range of insentivity, in this case 100 volts to 130 volts. The variation in the output meter reading is noted. A small capacitance is placed across one of the 800 turn windings on one of the reactors. When rebalanced with resistance, the sensitivity to line voltage variation is again checked. If the variation in the output meter reading is reduced for the swing in line voltage the capacitance is on the right reactor and only the proper value of capacitance remains to be determined. When the proper values of capacitance and resistance are obtained, the output, with zero input, will be insensitive to changes in line voltage over the range from 100 to 130 volts. To prevent the use of reactors that are too greatly mismatched, the values of trimming resistance and capacitance are limited. The capacitance should not exceed .0015 microfarads and the resistance should not be below 100,000 ohms.

32. The gain curve of the two stage connection of figure 9 is now checked and should fall in the range indicated in figure 10.

33. The final test of Stage I is to check its drift (output

for no input) over the temperature range of -55°C to +71°C.
Again, connected as in figure 9, and with the signal input
shorted, Stage I is placed in the temperature chamber. Some
provision, such as sealing in a container, must be made to
prevent moisture condensation on the components of Stage I.
Very large drifts are encountered when this precaution is
not taken.

34. The open loop drift vs temperature curve for Stage I is
plotted. Two examples are shown in figure 11, where the
closed loop drift for Stage I is also given for comparison
with the specified open loop drift. It is to be noted that
they correlate within a small fraction of the drift specifi-
cation. This drift will be in the order of 0 - 0.1 volts and
will be placed in opposition to a drift of roughly the same
magnitude in Stage II to insure drifts below the 0.05 volt
level. (Actually 90% of the samples investigated had less
than 0.05 volts drift alone when the procedure requirements
were followed.)

35. The facility with which these curves can be taken is seen
when it is pointed out that these are all open-loop measure-
ments requiring only an output meter in the way of instrumen-
tation. Large numbers of stages can be run simultaneously in
one temperature chamber requiring only a meter reading on
each at a given temperature.

ASSEMBLY AND TESTING OF STAGE II

36. A similar assembly and testing procedure to that of
Stage I is followed for Stage II. Stage II is assembled and
cascaded with a "standard" Stage I (assembled from matched
components) as shown in figure 12. While connected in this
manner the two stage circuit is trimmed for voltage insensi-
tivity in the same manner as that outlined in Assembly and
Testing of Stage I. The trimming, it will be noted, is applied
to the "standard" Stage I and the same limits to the amount
of trimming, namely, less than .0015 microfarads and no less
than 100,000 ohms, apply. Trimming in excess of this indicates
that the Stage II under test is too greatly mismatched to be
used.

37. Again the gain curve of the two stages is obtained and
must fall, in the range given in figure 10. The gain curve
test ordinarily should not result in any rejects at this
point in the assembly process.

38. An open loop drift (output for no input) curve for the
temperature range of -55°C to +71°C is now taken with the

Stage II in the temperature chamber. Again precaution must
be taken to prevent moisture condensation on the components.
This curve will be similar to the sample curve of a Stage II
given in figure 13 where the closed loop drift for the Stage
II is also given for comparison. The maximum drift will be
in the order of 0-0.1 volts and will be opposed to the drift
of a Stage I to produce drifts below the 0.05 volt level.

39. Again it should be pointed out that in a production set-
up, large numbers of stages can be run simultaneously in a
temperature chamber requiring only a meter reading on each
at the desired temperatures.

COMBINING STAGES I AND II

40. The testing of Stages I and II yields a drift curve for
each stage. The two stages which are to be used together are
selected on the basis of the magnitude of their drift curves.
Stages are chosen with drift curves that when subtracted
from each other fall well below the 0.05 volt level. This is
relatively easy since all the drift curves should be below
the 0.1 volt level. If the curves run on the test circuits
of figures 9 and 12 have drifts opposite in polarity, then
the output terminal A of Stage I is connected to input termi-
nal A' of Stage II and B is connected to B'. This results
in subtraction of the drifts. If the curves run on the test
circuits of figures 9 and 12 have drifts of the same polarity
then the output terminal A of Stage I is connected to the
input terminal B' of Stage II and the output terminal B of
Stage I is connected to input terminal A' of Stage II. This
again results in subtraction of the drifts.

41. The two stages are wired together at this point and remain
together when inserted in the completed unit. Again it is
advisable as a production check to take a gain curve of the
two stage amplifier.

ASSEMBLY AND TESTING OF STAGES III AND IV

42. The selection of components and the assembling of Stages
III and IV requires no special technique. The Orthonol tape
cores should have gain properties as good as those described
in Stage II for satisfactory performance. As stated previously
although Radio Receptor Company rectifiers gave the desired
results, other rectifiers may be substituted so long as
amplifier performance (gain and time delay) are unimpaired.

43. It may be advisable to temperature cycle the rectifiers and
reactors as done for Stage II to stabilize them as far as possible.
The rectifiers should afterwards be formed for 24 hours at

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rated current and voltage.

44. With the input to Stage III shorted through its 1000 ohm input resistance, any unbalance in Stages III and IV can be removed by shunting a winding on a reactor of Stage III with a high resistance. The gain of these two stages should be checked and should be approximately that of the gain curve in figure 14 or higher.

FINAL ASSEMBLY

45. The combined first and second stages are now assembled with stages III and IV. The final adjustments are made after the servo loop is closed. There are two adjustments to be made which interact somewhat. The feedback around Stages I and II must be set by means of the voltage divider on the output of Stage II. This is adjusted until the running error is below 0.1 volts for both directions of rotation and for all speeds up to 20 degrees per second at the control transformer shaft. If a static error is present, allowance must be made for this error while measuring the running error. The adjustment of the voltage divider may have a slight effect on the static null error. When the divider is set the final balancing is accomplished by means of resistance and capacitance shunt on a reactor of Stage I. It will be recalled that such a balancing and voltage insensitizing procedure was carried out in the assembly and testing of Stage I. The capacitance and resistance shunts if still present on Stage I may have to be adjusted in this final balancing and voltage insensitizing check.

46. The amplifier is now completed. A block diagram of the construction schedule is shown in figure 15 which will summarize the steps taken.

CONCLUSIONS

47. Input stage circuit components operate in such a non-linear manner and require such sensitive matching that they must be selected by comparison under actual circuit conditions.

48. The remaining stages can be drift insensitized by nominal selection of components.

49. This procedure though moderately complicated is of such a nature as to make possible the practical manufacture of drift insensitive, high performance, magnetic amplifiers.

50. Though outlined for one specific circuit this procedure with slight modifications is applicable to all high performance magnetic amplifiers.

APPENDIX

OUTLINE OF DRIFT INVESTIGATION PROGRAM

1. When the study of drift in magnetic amplifiers was under-
taken, preliminary tests indicated that the three main sources
of drift were (1) disturbances causing unbalanced operation
of rectifiers, (2) disturbances causing unbalanced operation
of reactors, and (3) disturbances causing a change in level of
operation of the rectifiers which changed the level of oper-
ation of the reactors, causing unbalanced operation. This
latter source of drift is difficult to detect because reactor
unbalance occurs when the rectifiers only are in the temper-
ature chamber.

2. The disturbances, causing drift, that are considered in
this drift study are temperature, voltage and frequency. To
simplify the investigation the assumption was made that fre-
quency variations could be roughly simulated by voltage
variations. Consequently the voltage variations were increased
in lieu of taking frequency tests. Spot checks taken later
verified the validity of this assumption.

3. The first investigations revealed considerable drift
contributed by the unbalanced operation of the rectifiers
over the temperature and voltage range. This was in con-
formance with the general experience in the field. First
emphasis therefore was placed on the minimization of drift
in the rectifiers of the first stage, which was a conventional
half-wave bridge.

4. An attempt was made to match rectifiers on the basis of
their voltage current characteristics. The rectifier reverse
current was measured at three voltage levels, the 0.5 volt
per plate, the 1.0 volt per plate and the 2.5 volt per plate
level. Variations of approximately 8% were noted. The for-
ward direct voltage on the rectifier was measured at six
different forward current levels, i.e., 1 ma, 2 ma, 5 ma,
20 ma, 50 ma, and 100 ma. Variations of approximately 10%
were noted in this region. When assembled stacks of recti-
fiers failed to produce any matched pairs, one hundred unassem-
bled one-inch-square selenium rectifier plates were measured
and stacks of 6 plates (12 plates doubler connected were
normally used in each side of bridge) assembled from selected
plates. No two plates had all nine readings identical but it
was possible to assemble stacks that had no differences great-
er than 5%. At this stage of the investigation two performance
tests were being used to indicate matched rectifier stacks.
One was to interchange the stacks in the bridge circuit. This
was later found to be misleading. The other was to measure
the drift over the temperature range. Both tests failed to

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give more than fair correlation with the voltage-current
measurements obtained on the rectifiers and the drifts
encountered over the temperature range were far in excess of
the 0.05 volt specification. The failure to correlate was
attributed to two causes. One, and most important, was the
failure of the rectifier voltage-current test circuit to
duplicate operating conditions. The other was the interaction
between rectifiers and reactors, particularly in the bridge
circuit, which made isolation of their respective drifts
difficult. Considerable effort was directed toward duplica-
ting actual operating conditions in the test circuit by the
addition of rectifiers and/or reactors, but little success
was achieved. The most practical method appeared to be to
match input stage rectifiers by comparison in the actual
magnetic amplifier circuit. This comparison was obtained by
interchanging rectifiers and noting circuit behavior under
each condition. In the bridge type circuit this interchange
yielded poor data due to the interaction among components.
The trouble arose from the inequality of the four legs of the
bridge. In order to effectively eliminate two legs of the
bridge the first stage circuit was changed to the differential
circuit where a half-wave magnetic amplifier stage is coupled
to the following stage by means of differential windings.
This circuit had been previously used in the Magnetics Division
of the Naval Ordnance Laboratory to obtain higher gains than
from the conventional bridge. It has also been suggested that
since the number of rectifiers was reduced over the conventional
bridge the matching should be easier. In addition the differ-
ential circuit permitted somewhat better control of distributed
capacitances because the reactor power windings were now
combined into one power winding. It should be noted here that
a large percentage of the leakage current in selenium recti-
fiers at 400-cycle power frequency is capacitive current and
that at the drift level required capacitive unbalance in
rectifiers and reactors causes considerable trouble. After
changing over to the differential circuit an effort was made
to correlate several types of absolute measurements on the
rectifiers with circuit performance, but without success.
From this point on, input stage rectifiers were matched only
by comparison in the actual differential circuit being used
but with the output differential windings replaced by 100 ohm
resistors. The circuit, however, still appeared to be far
too sensitive to rectifier mismatch. To insensitize the cir-
cuit to the effects to rectifier mismatch a rectifier was
added in the line feeding the differential stage. A large
number of plates were used in this rectifier which was common
to both legs of the differential circuit and the effect was
to minimize reverse leakage differences in the rectifiers in
each leg of the circuit. To reduce resetting action from

rectifier reverse leakage the reactors were wound with a
relatively few number of turns. The line resistance was
added to reduce quiescent current with its attendant heating
drift and to minimize the effect of forward resistance dif-
ferences in the rectifiers in each leg of the circuit.

5. Using the differential circuit with line rectifier and
selecting leg rectifiers by comparison in the actual circuit,
drift due to rectifier unbalance was minimized. As previously
mentioned, however, this rectifier drift was not completely
distinguishable from reactor drift. When the temperature is
changed the impedances of the rectifiers change and these
changes in impedance, quite apart from mismatch in impedance,
change the flux setting on the reactors. The operation of the
reactors around a new flux level brings out mismatch in the
reactors not present when operating around the former flux
level. Thus, with the rectifier only in the temperature
chamber, the drift recorded may be due solely to reactor mis-
match. This would seem to indicate that the reactors only
should be placed in the temperature chamber to record strictly
reactor drift. However, when the temperature is changed
under these conditions the coercive force of the reactor core
changes, the firing angle, or point of saturation in the half
cycle of line voltage, also changes. This new firing angle
on the conducting half cycle and changed impedance on the
reset half cycle cause changed waveforms to be placed on the
rectifier. The new waveforms with their associated harmonics
bring out mismatches in the rectifiers not seen under previous
conditions. Thus with the reactors only in the temperature
chamber mismatch in the rectifiers may be contributing to the
recorded drift.

6. As a result of these effects it was not possible to say
with certainty that the drift due to rectifiers had been
reduced to some specific value even after the above discussed
changes were made. It was necessary to assume for the moment
that rectifier drift had been minimized and to direct the
effort toward minimization of drift in the reactors of stage
one.

7. Considerable drift apparently was being contributed by the
reactors. Selection on the basis of B-I curves did not yield
the quality of matching necessary to guarantee low drift over
the temperature range. This was attributed to the mechanical
construction of the Orthonol tape-wound toroids which are
subject to some mechanical stress under ambient temperature
changes. To overcome this, laminated core material was adopted.
It should be pointed out that as time was limited a full
investigation of this problem of core construction could not

be carried out and subsequent experimentation may show the
suitability of tape-wound toroids for operation over a large
temperature range.

8. With laminated 4-79 molybdenum permenol cores in differen-
tial circuit connection plus line rectifier and selected leg
rectifiers, the drifts experienced with the entire Stage I
in the temperature chamber were now in the order of 0.1 volt.
With this low temperature drift the most pronounced drift
experience in the amplifier was now due to line voltage vari-
ations. For a line voltage variation of 100 to 130 volts
drifts of several times the 0.05 volt specification were
noted.

9. It was known that in the half-wave bridge magnetic ampli-
fier the series-type reset circuit[3] was less sensitive to
line voltage variations than the parallel-type reset circuit.
Accordingly, the first three stages of the amplifier under
study were converted to series-type reset. This involved
shunting the doubler connected rectifier in one side of the
bridge for Stages II and III and changing the circuit in
Stage 1. It had been previously noted that sensitivity to
line voltage variation was affected by the balancing method
used. A study was undertaken that resulted in the resistance-
capacitance trimming method[4] for decreasing the sensitivity
to line voltage changes. By following this method, which is
outlined in the main body of this report, the line voltage
drift can be reduced to a small fraction of the 0.05 volt
total drift specification. Although the trimming technique
fails to maintain the same voltage insensitivity over the
temperature range it does reduce it to such a low value that
it no longer is an appreciable amount of the 0.05 volt speci-
fication.

10. With the minimization of the voltage and temperature
drifts in Stage I the open loop drift problem was essentially
solved. The drift contributed by Stage II was an order of
magnitude lower and it was assumed at this time that nominal
selection of components for this stage and succeeding stages
would be satisfactory.

11. It was now necessary to investigate the closed loop
system where additional feedback connections were made, where
the first two stages function as an integrator and where the
low velocity error specification must be met, requiring near
constant gain in the first two stages. These additions to
the problem had to be met over the temperature range and for
required variations in line voltage.

12. Upon placing the positive integral feedback around the first two stages and closing the servo loop an unbalance was introduced. If the amplifier was rebalanced under these conditions the gain curve was distorted to cross the origin and remained unchanged at higher levels. This caused the gain curve to be non-linear and adversely affected the operation of the integrator. The unbalance introduced when the positive integral feedback loop was closed was due to distributed capacitance between the power winding and the control winding on which the feedback signal was placed. To prevent this the windings on the reactors of Stage I were sector wound and the feedback circuit made as symmetrical as possible. This resulted in essentially the same balance in both open and closed loop.

13. To assure meeting the low velocity error specification under all conditions, extensive dynamic tests were run at room temperature before any tests were run at different ambient temperatures. In these tests the slope of the gain curve and linearity of the gain curve sufficient to maintain near zero velocity error over the line voltage range of 100-130 volts were found. The velocity error was measured for six input velocities: 20 degrees per second at the control transformer shaft, 12 degrees per second, 5 degrees per second, -5 degrees per second, -12 degrees per second, and -20 degrees per second. This was repeated for each of the three line voltage levels, 100 volts, 115 volts, and 130 volts. This data was taken using fourteen different input stages after determining that the remaining three stages of amplification were satisfactory. The fourteen input stages were provided by first running one set of rectifiers with six different sets of reactors and then running one set of reactors with eight new sets of rectifiers. The results obtained were limits on the slope and linearity of the gain curve, necessary relative matching of reactors, and necessary relative matching of rectifiers.

14. After determining the requirements for room temperature operation the tests were repeated at the six velocities and three voltage levels for ambient temperatures of $0^{\circ}C$, $-25^{\circ}C$, $-50^{\circ}C$ and $+75^{\circ}C$. This data was taken using six different first stages where the first stage only was placed in the temperature chamber, and for two second stages, where the second stage only was placed in the temperature chamber. This data was not as good as expected, being slightly outside the 0.05 volt specification for several of the stages. This was attributed to moisture condensation on the components and subsequent tests verified this. Up to this point, in all cold temperature tests the amplifier had been placed in a

sealed plastic bag containing a drying agent. However,
air leakage around the lead-in wires permitted sufficient
moisture to condense on the amplifier to cause a drift in
the order of the 0.05 volt specification. This drift was
not identified as moisture drift but was assumed to be tem-
perature drift. To correct this when it was discovered, the
amplifiers were placed in metal containers having press tight
lids equipped with lead-in headers. The seams were soldered
thoroughly and the lid was sealed with Glyptol after a drying
agent, Calcium Hydride was placed in the container. When the
amplifiers were operated in this manner the drifts were
reduced still further and were in the range expected.

15. The second stage drift appeared to be lower than the 0.05
volt specification as long as components were nominal. However,
the drift was an appreciable fraction of the 0.05 volt allow-
able drift. This plus the fact that the input stage drift was
marginal if high yields were expected indicated that a higher
yield could be obtained and considerably lower drifts would
result if the drift of Stage II was made to oppose the drift
of Stage I. This could be accomplished by the fairly simple
expedient of taking an open loop drift curve during fabrication
of the particular stage, and upon assembly of the unit, connec-
ting the stages so as to oppose the drifts.

16. The requirements on the amplifier were now well under-
stood and specifications had been set on all components, gains,
and linearities. Many specifications were satisfactory, while
at the same time it was realized that they could be loosened
when additional data were obtained on larger statistical samples.
Since the purpose of the investigation was to show the practi-
cability of manufacturing a drift insensitive magnetic control
amplifier, it was felt that the first emphasis should be on
completely specifying the problem and making conservative
estimates of yields on components. Further experience on the
part of the manufacturer should liberalize specifications and
increase yields.

17. As a final check on the procedures outlined in the main
body of this report a sample consisting of ten input stages
and 4 second stages were tested under humidity free conditions
and at the ambient temperatures, +75°C, +50°C, +25°C, 0°C,
-25°C, -55°C. At each temperature the static error was checked
for line voltages of 100v., 115v., and 130v. The velocity
error was checked for the three line voltages with the six
input velocities discussed previously. In addition, the open
loop gain curve of Stages I and II was taken at each temper-
ature. Each amplifier stage was allowed to stabilize at each
new temperature for at least seven hours. The results of
these tests gave further verification to the specifications

outlined. Figure 11 is a sample of the type of drift curve obtained from these tests.

18. As a result of this drift study the foregoing preliminary specifications and techniques for manufacturing drift insensitive magnetic control amplifiers were devised. The procedure outlined is considerably simpler than some manufacturing procedures now in use in this field and subsequent study should serve to further simplify it.

REFERENCES

1. C. W. Lufcy, A. E. Schmid, and P. W. Barnhart "An Improved Magnetic Servo Amplifier" Technical Paper 52-235, <u>AIEE Transactions</u> Sept 1952.

2. H. H. Woodson, "Magnetic Amplifier Servo Compensation" NavOrd Report 2709

3. H. H. Woodson, "Preliminary Analysis of the Half-Wave Bridge Magnetic Amplifier" NavOrd Report 3596.

4. H. H. Woodson, E. T. Hooper, "External Trimming to Reshape the Hysteresis Loop of a Saturable Reactor" NavOrd Report 3564.
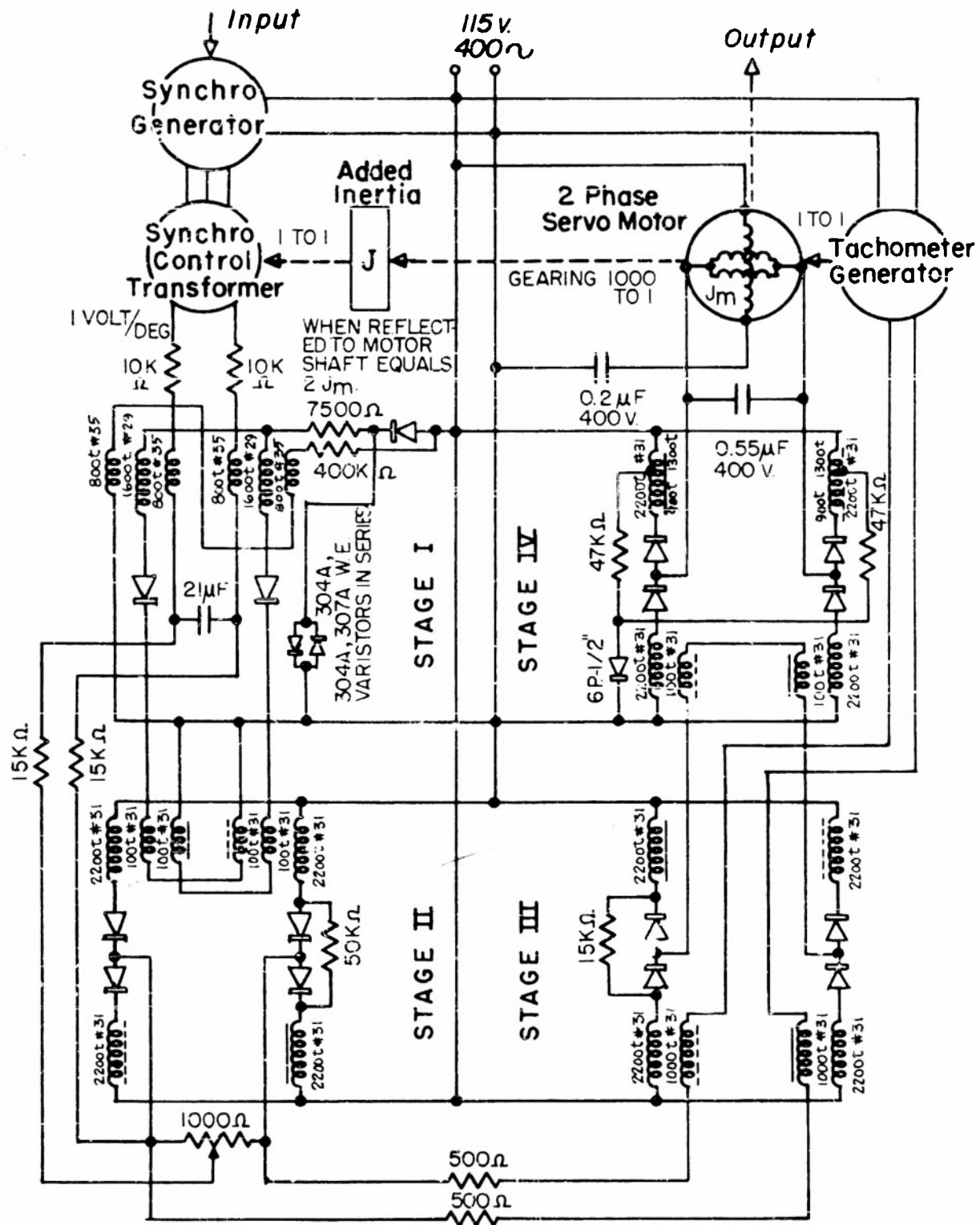
FIG. I — COMPLETE CIRCUIT DIAGRAM

FIG. 2 — SECTOR WINDING LAYOUT

FIG. 3 — TEST CIRCUIT FOR STAGE I COMPONENTS
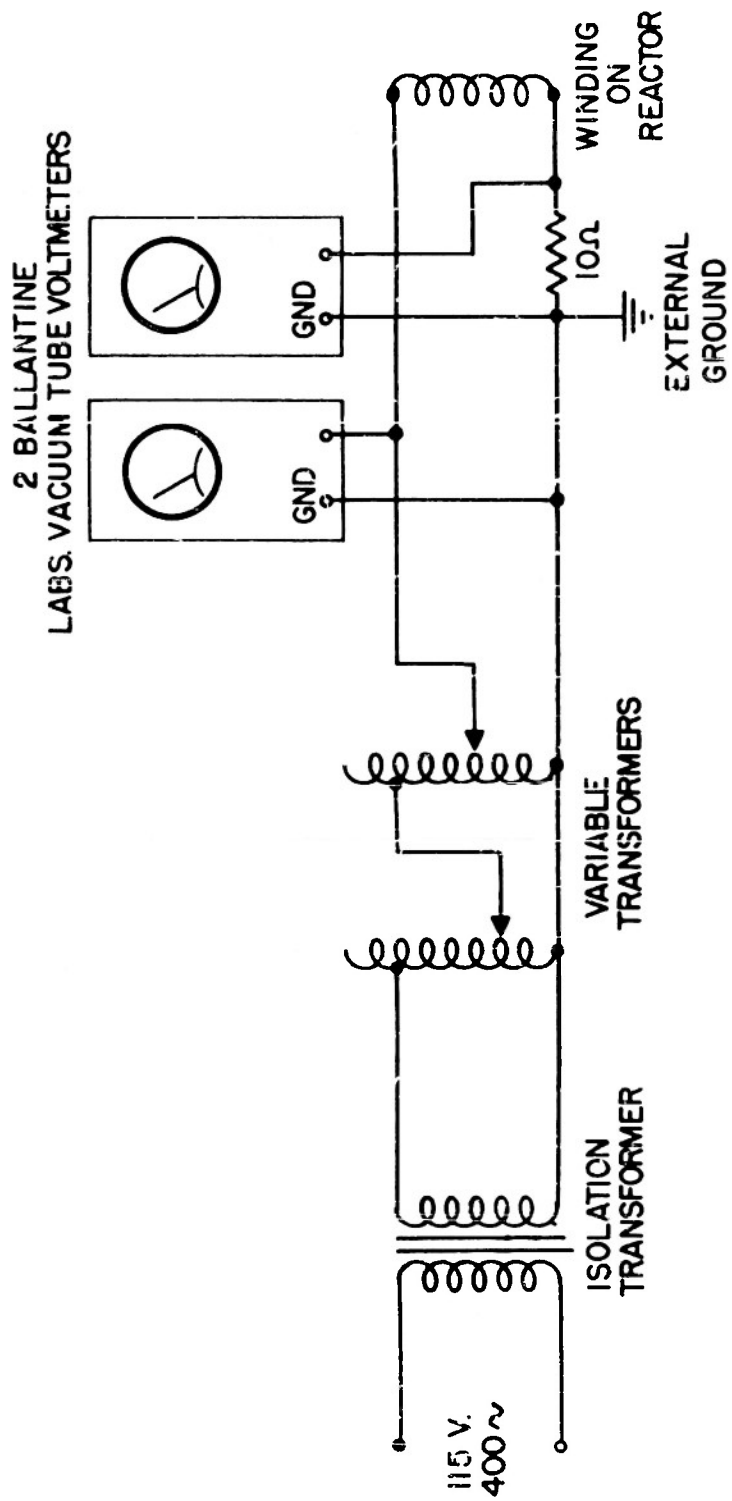
FIG. 4 – TEST CIRCUIT FOR MEASURING E–I CURVES

MEASURED ON TEST CIRCUIT OF FIGURE 4
USING 800 TURNS ON REACTOR
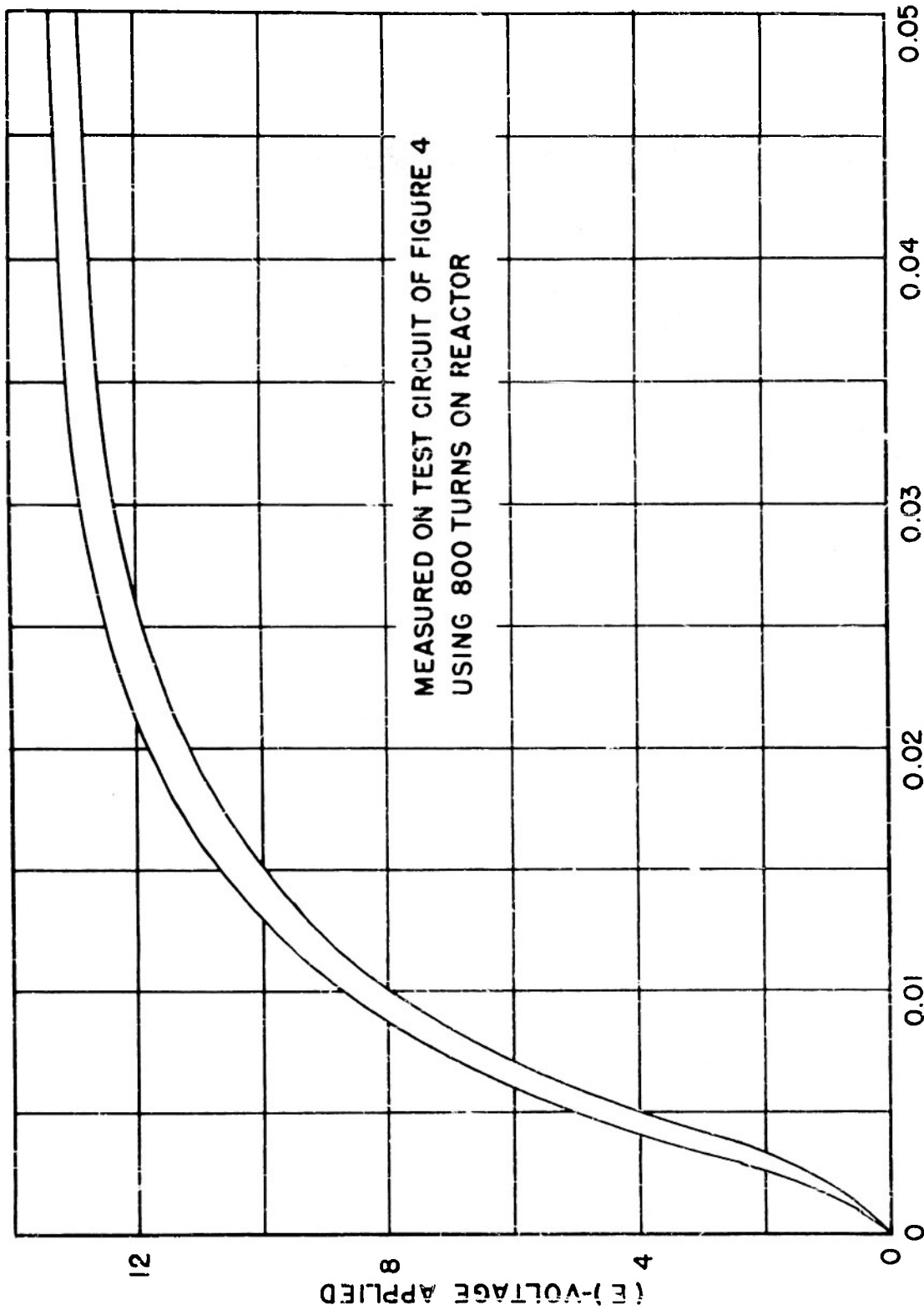
(I)-VOLTAGE ACROSS 10Ω RESISTOR

FIG. 5 - ALLOWABLE E-I CURVE FOR STAGE I REACTORS
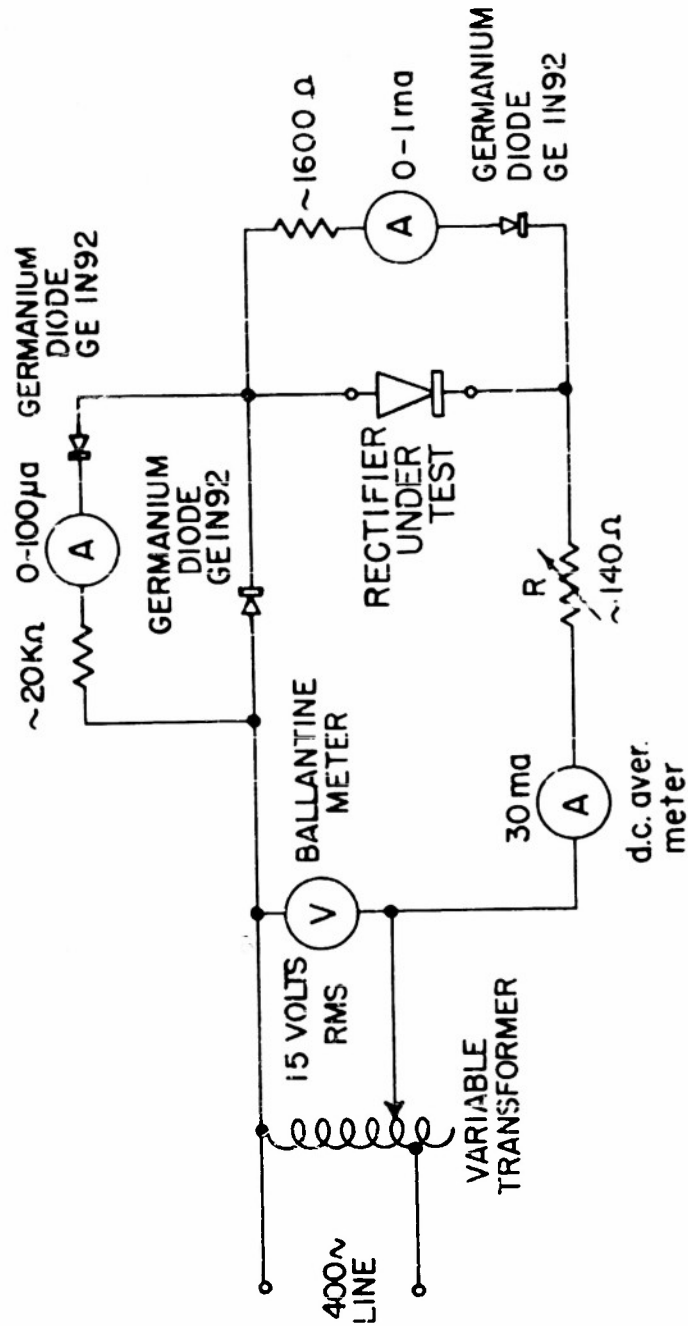
FIG. 6 – TEST CIRCUIT FOR STAGE II RECTIFIERS

25

RED YELLOW BLACK
LUG LUG LUG

RED YELLOW BLACK
LUG LUG LUG

BASE PLATE
SELENIUM

NOT ACTUAL SIZE
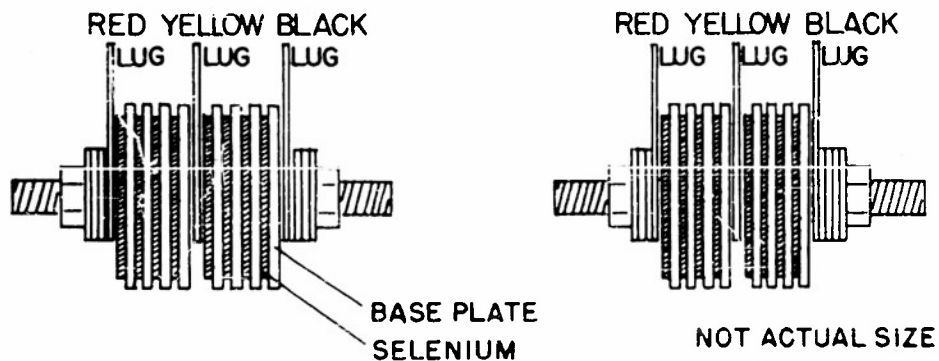
IT IS NOT NECESSARY TO MATCH
ALL FOUR SECTIONS WITH EACH
OTHER.

THE RED-YELLOW SECTIONS OF
EACH MUST BE MATCHED WITHIN
THE SPECIFICATIONS IN BOTH
METER READINGS.

THE YELLOW-BLACK SECTIONS
OF EACH MUST BE MATCHED WITH-
IN THE SPECIFICATIONS IN BOTH
METER READINGS.

FIG.7 - DOUBLER CONNECTED RECTIFIER MATCHING
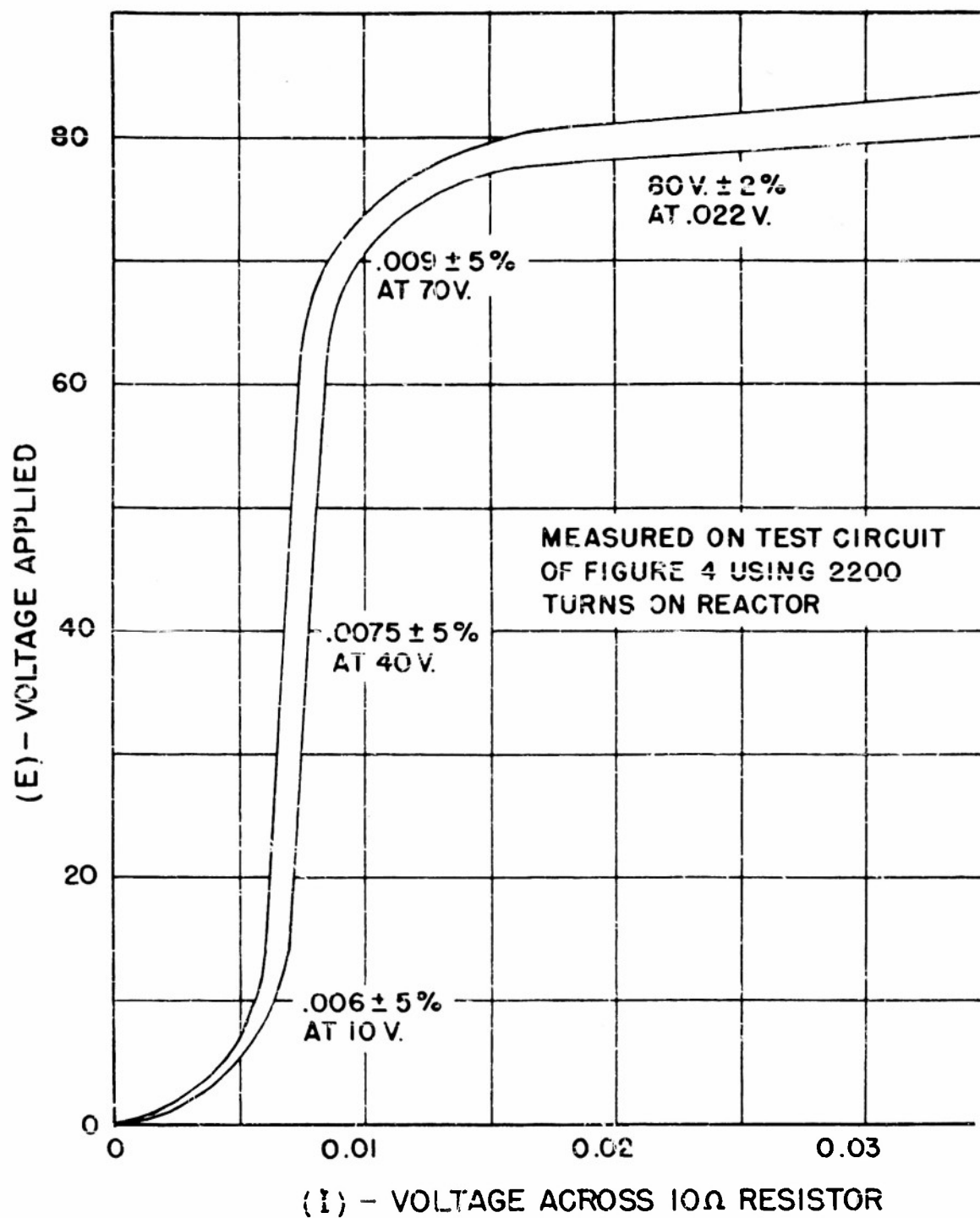
FIG. 8 – ALLOWABLE E-I CURVE FOR STAGE II REACTORS
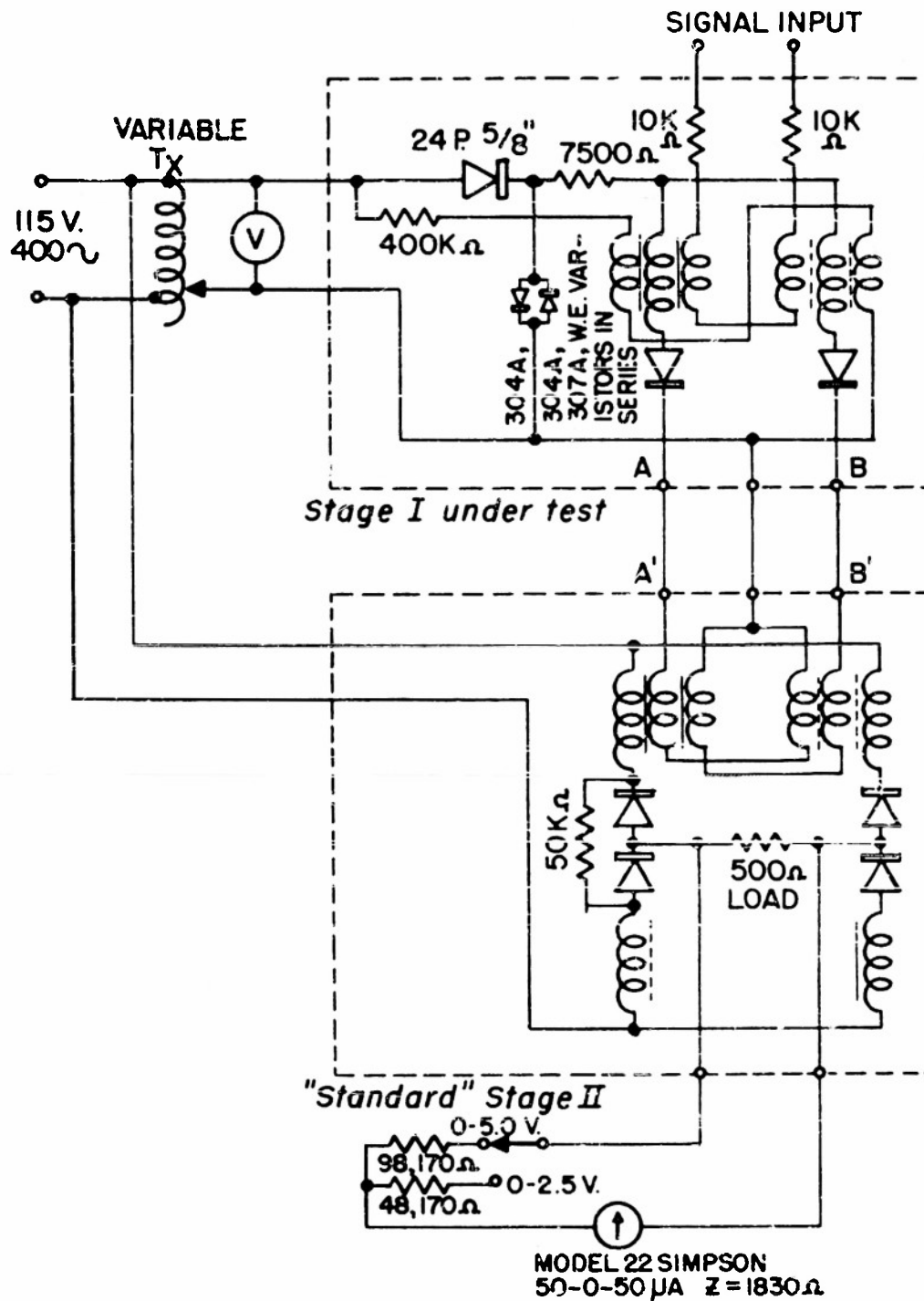
FIG. 9 — TEST CIRCUIT FOR STAGE I
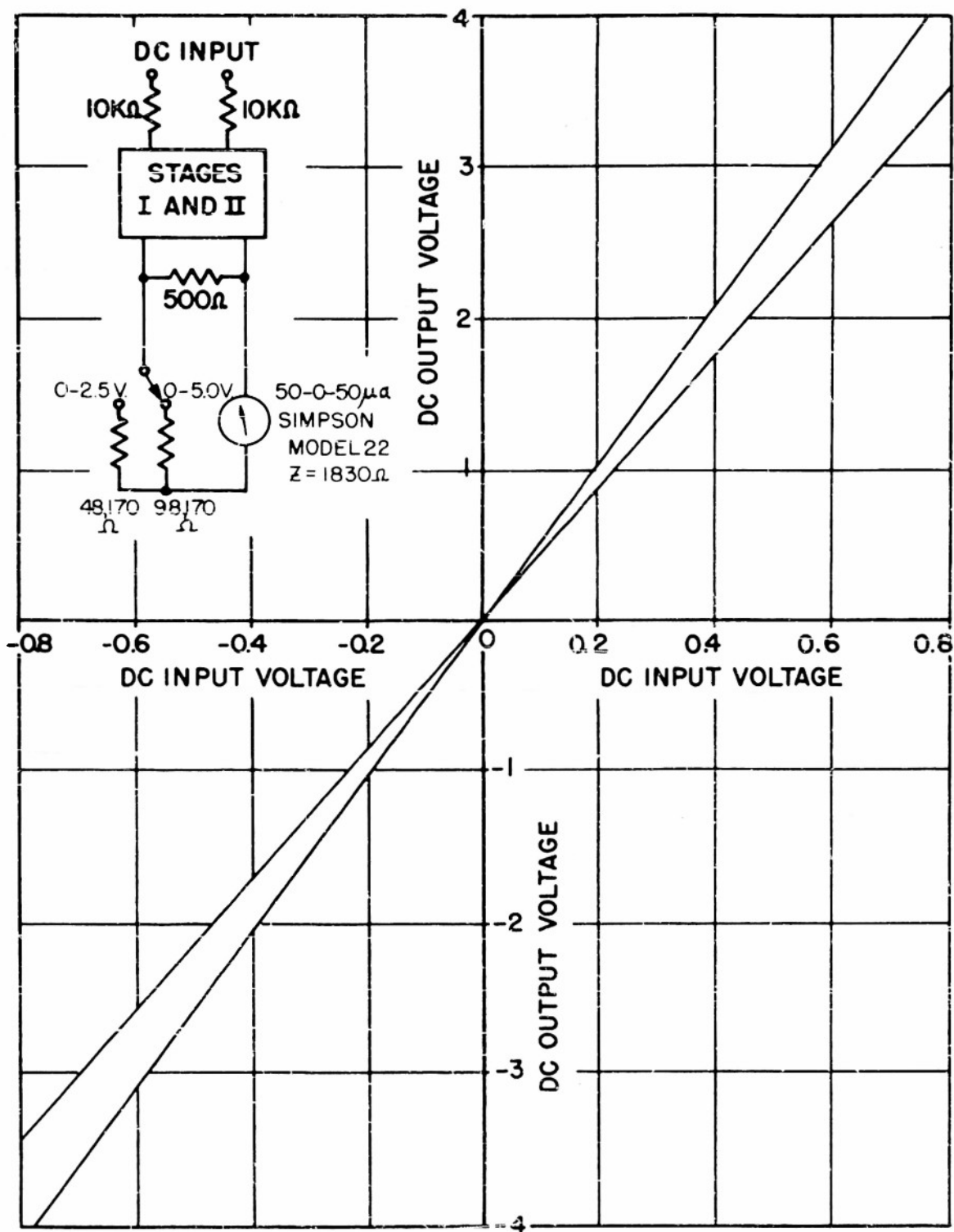
FIG. 10 - GAIN CURVE FOR FIRST TWO STAGES
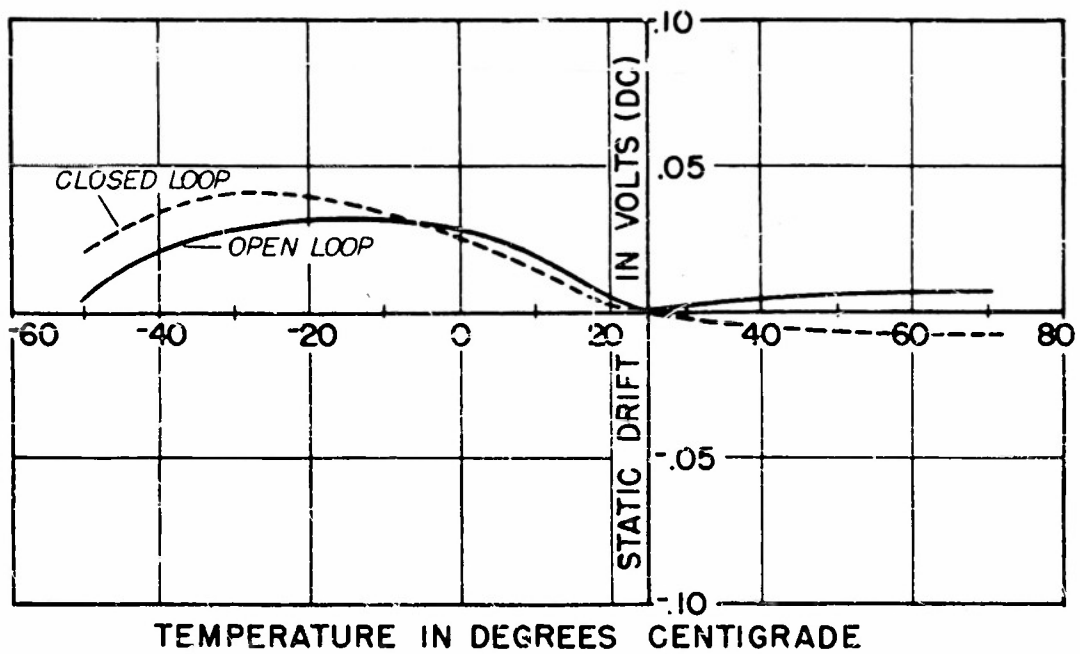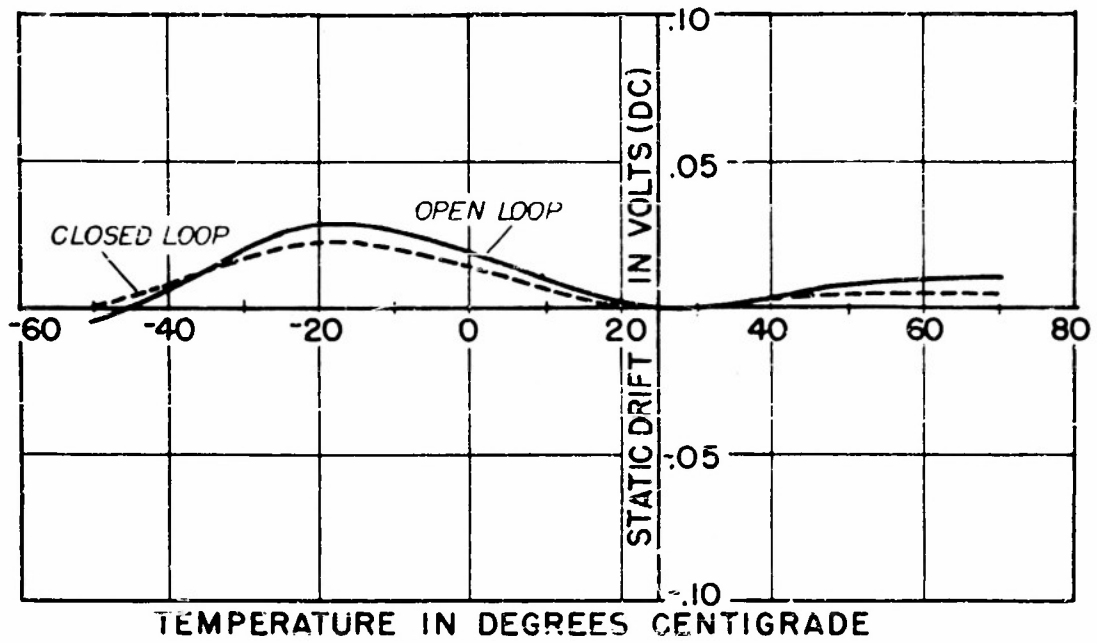
FIG.11 — DRIFT OF SAMPLE FIRST STAGES
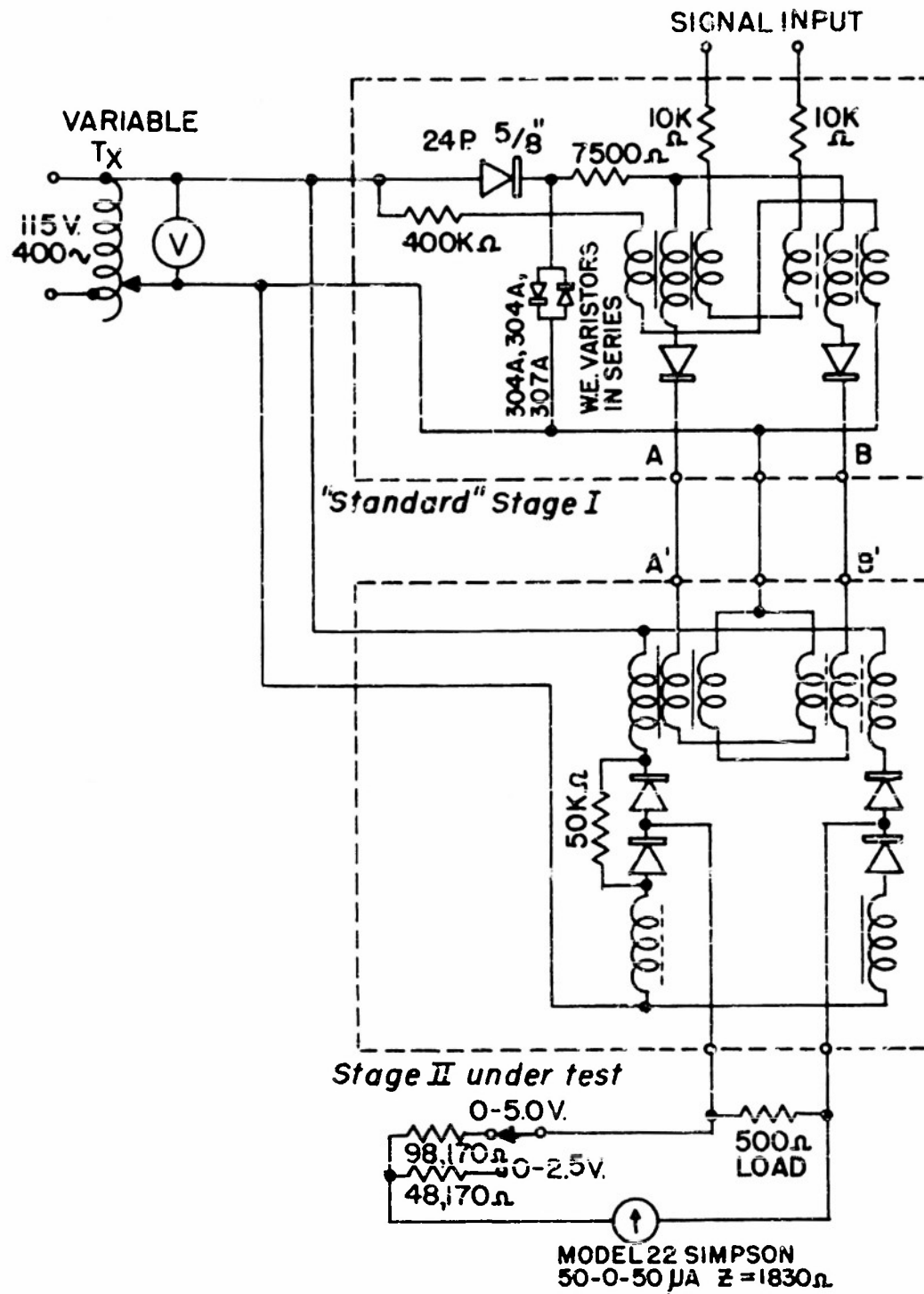
FIG. 12 — TEST CIRCUIT FOR STAGE II
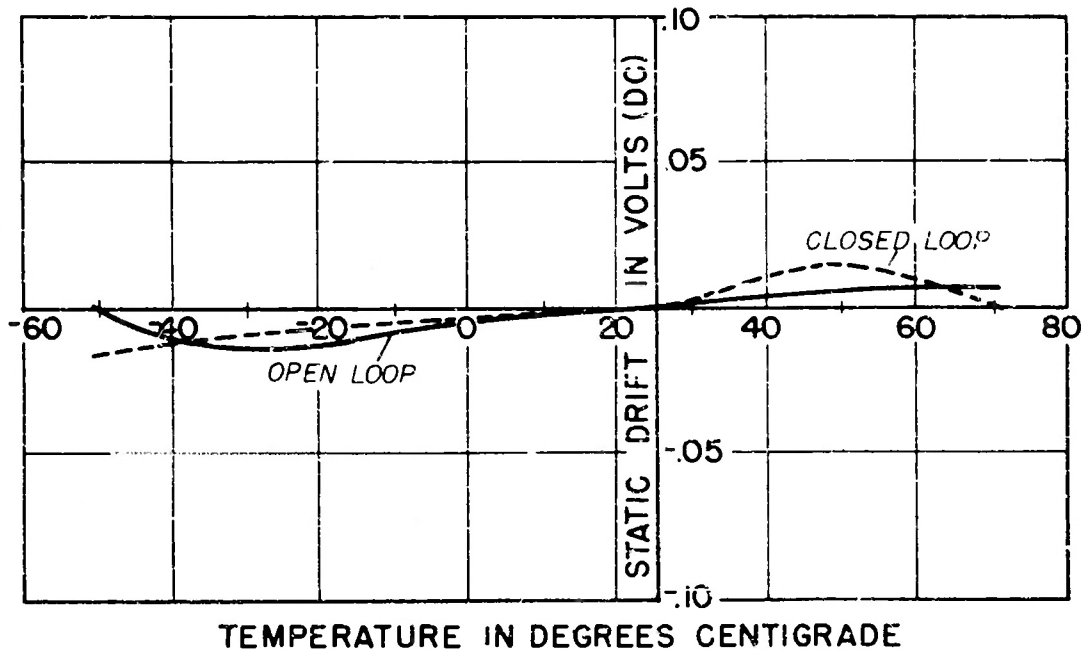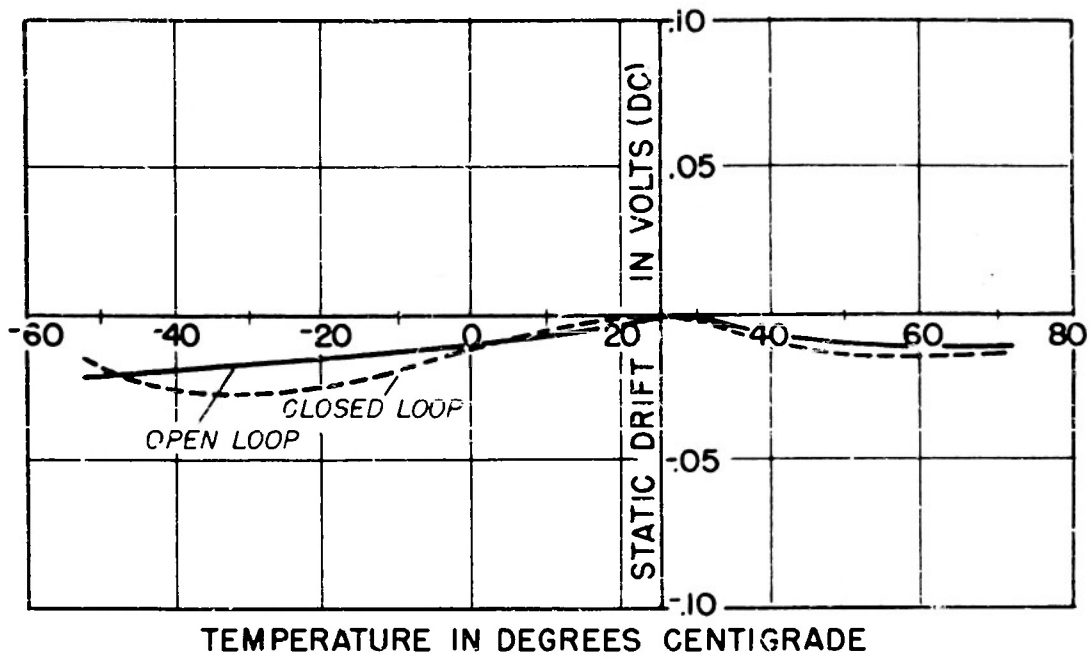
FIG. 13 - DRIFT OF SAMPLE SECOND STAGES
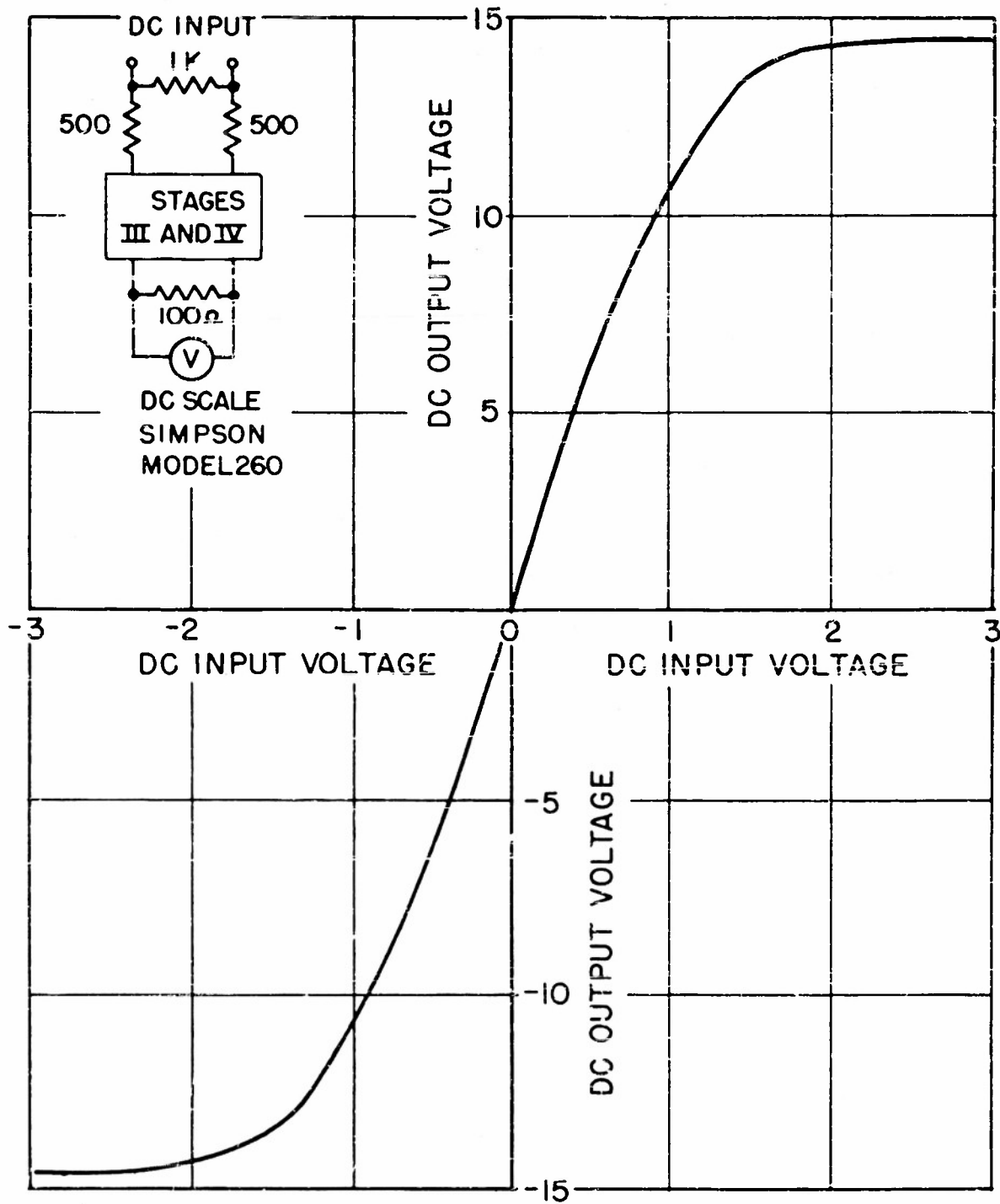
FIG. 14 — GAIN CURVE FOR LAST TWO STAGES

```
┌─────────────────┐
│    SELECTED     │
│   CORES FOR     │
│    STAGE I      │
│     FROM        │
│  TEST CIRCUIT   │
└─────────────────┘
                          ┌─────────────────┐
                          │    ASSEMBLY     │
                          │      AND        │
┌─────────────────┐       │   TESTING OF    │
│    SELECTED      │      │    STAGE I      │
│  RECTIFIERS FOR  │      └─────────────────┘
│    STAGE I       │
│     FROM         │                           ┌─────────────────┐
│  TEST CIRCUIT    │                           │  COMBINATION    │
└─────────────────┘                            │   OF STAGES     │
                                               │   I AND II      │
┌─────────────────┐                            └─────────────────┘
│    SELECTED      │
│   CORES FOR      │
│    STAGE II      │
│     FROM         │
│  WEIGHTS AND     │       ┌─────────────────┐
│  E-I CURVES      │       │    ASSEMBLY     │
└─────────────────┘       │      AND        │
                          │   TESTING OF    │
┌─────────────────┐       │    STAGE II     │
│    SELECTED      │      └─────────────────┘
│  RECTIFIERS FOR  │                           ┌─────────────────┐
│    STAGE II      │                           │    COMPLETE     │
│     FROM         │                           │    SYSTEM       │
│  TEST CIRCUIT    │                           │       —         │
└─────────────────┘                            │    FINAL        │
                                               │  ADJUSTMENTS    │
┌─────────────────┐                            └─────────────────┘
│    ASSEMBLY      │
│   OF STAGES      │
│  III, IV, AND    │
│  MECHANICAL      │
│   SYSTEMS        │
└─────────────────┘
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FIG. 15 — FABRICATION PROCEDURE

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